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In this report, we outline the design considerations and construction of an EUV reflection imaging microscope. The parameters of the microscope and the debris measurements of the source are presented. The reasons for selecting a laser-produced plasma (LPP) source and a Schwarzschild objective are described. While most research efforts for the development of soft-x-ray sources such as soft-x-ray lasers pursue the generation of shorter and shorter wavelengths down to the "water window", the EUV and soft-x-ray spectral regions are also ideal wavelengths for applications in chemistry and biology due to the photon energy being close to the molecular bond energy[2].
In this report, we outline the design considerations and construction of an EUV reflection imaging microscope. The parameters of the microscope and the debris measurements of the source are presented. The reasons for selecting a laser-produced plasma (LPP) source and a Schwarzschild objective are described. While most research efforts for the development of soft-x-ray

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**Final Technical Report - Contract F49620-92-J-0405**

Simplified

# "ULTRA-HIGH RESOLUTION OPTIC FOR SOFT-X-RAY IMAGING"

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**Submitted by**

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## 1. INTRODUCTION

Soft-x-ray microscopy is advancing as a prospective technology due to the recent improvement of soft x-ray optics and high brightness x-ray sources. It would offer an advantage over an optical microscope by providing both ultra-high resolution and good depth of focus combined with an extremely short exposure period[1]. Our objectives are to design and develop a soft-x-ray reflection imaging microscope using a compact laser-produced plasma source and a normal incidence multilayer-coated Schwarzschild optic, and to use the microscope to obtain ultrahigh resolution images at high magnification with good fidelity and high sensitivity. The initial project is three fold: (1) making image contrast measurements to help determine the optimum wavelength for the operation of the microscope, (2) making resolution measurements with an extreme ultraviolet (EUV) microscope, and (3) designing a new off-axis partial Schwarzschild optic to use for imaging in the 13 - 20 nm spectral region. The development of a soft-x-ray microscope will have important applications in biological and material sciences, ranging from observations of various types of organic specimens including living cells, to the high-resolution examination and inspection of surfaces including those associated with microchips and other materials having fine-featured patterns.

In this report, we outline the design considerations and construction of an EUV reflection imaging microscope. The parameters of the microscope and the debris measurements of the source are presented. The reasons for selecting a laser-produced plasma (LPP) source and a Schwarzschild objective are described. While most research efforts for the development of soft-x-ray sources such as soft-x-ray lasers pursue the generation of shorter and shorter wavelengths down to the "water window", the EUV and soft-x-ray spectral regions are also ideal wavelengths for applications in chemistry and biology due to the photon energy being close to the molecular bond energy[2].

## 2. THE LASER PLASMA SOURCE

A suitable source for an imaging x-ray microscope should be a pulsed source with a duration on a time scale that is short compared to the time required for radiation to damage the sample. The recent improvement of high brightness and short pulse duration of laser-produced plasma (LPP) x-ray sources provides unique advantages for an x-ray microscope[3-5], especially for use in single shot x-ray microscopy. Therefore sufficient energy can be obtained over a short time period and a short pulse length offers the potential of observing a living sample before x-ray exposure damge occurs. Our laser plasma source is well suited to the needs of a reflection imaging microscope as the pulse length (10ns) and pulse energy (500mJ) of the laser are sufficient to record an EUV or soft-x-ray image of a specimen in a single shot. The LPP soft-x-ray source is formed by focusing the 10ns duration laser onto a 1.5mm diameter tantalum rod at an intensity of the order of $10^{11}$-$10^{12}$ W/cm$^2$.

The laser plasma irradiance is dependent upon both the specific target material and the laser intensity.The emission of a LPP is found to be sensitive to the laser intensity and can be characterized by a temperature associated with that of a blackbody radiator[6]. In the EUV region of 50-60nm (photon energy 20eV), for a 250μm diameter 20eV plasma emitting for a duration of 10ns, the theoretical flux would be 145.6mJ/cm$^2$ in a 10nm bandwidth into 0.26 steradian for a single pulse, as shown in Figure 1.

Based upon theoretical estimates, the flux limiting element in a soft-x-ray reflection imaging microscope is the illumination flux loading on the sample. It is desirable to operate the microscope with illumination levels near this maximum flux loading for several reasons. First, it would be preferable to obtain an image with only a single 10 ns laser-plasma illumination pulse. This would allow image acquisition in a time frame that would minimize image blurring and distortion due to movement and vibration. It would also improve the image acquisition data rate, especially if this microscope were to eventually be incorporated into an automated mask or chip inspection system in which a large number of separate images are taken over an entire sample. Second, it would minimize the total number of laser plasma pulses required. This would simplify the laser-plasma source design by (i) minimizing the debris produced by the source, thereby reducing the potential damage to the illumination optics, and (ii) simplifying the laser plasma target system design that must provide a new plasma target for each laser pulse.

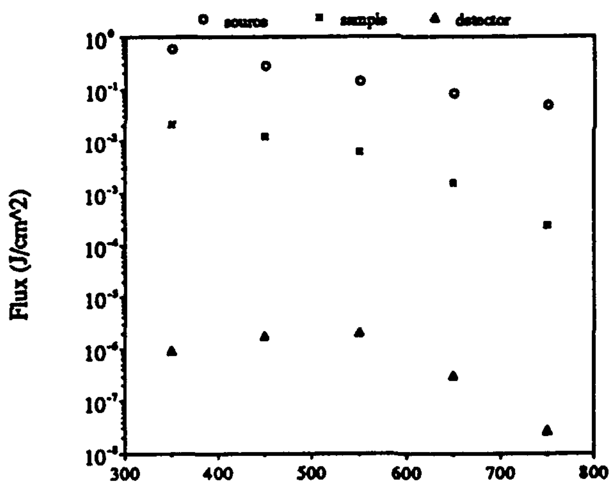


Figure 1. The theoretical flux for a single pulse 20eV laser plasma in a 10nm bandwidth. Laser energy is 500mJ with 1.06μm wavelength and 10ns pulse duration, and focal spot diameter is 250μm.

Operation near the damage threshold would be required for single pulse image acquisition. Preliminary estimates suggest that fluxes in the range of 10mJ/cm$^2$ might be safe for sample illumination, but there are significant uncertainties regarding absolute absorption and reflectivity of the material components of those samples in the wavelength region under consideration for operation of the microscope. In addition, the considerations of surface scattering and heat conduction must be taken into account for various sample geometries, such as narrow conducting lines and transistor gates for example, that might be more easily damaged by excessive heating. The unwanted part of the radiation could be reduced before arrival at the sample by either using a broadband filter, in which case there is still a significant amount remaining within the filter bandwidth, or using a second illuminating mirror, which serves as a filter but also effectively reduces the total flux at the desired wavelength. In our case, both an illuminating mirror and an EUV/soft x-ray filter are used to filter away the excess background radiation.

## 3. THE SCHWARZSCHILD OBJECTIVE

The initial Schwarzschild objective is a design that has been used for years in ultraviolet and infrared microscopy. It can also be a powerful microscope objective in the soft-x-ray spectral region when used in conjunction with a LPP source. In fact, It has been used

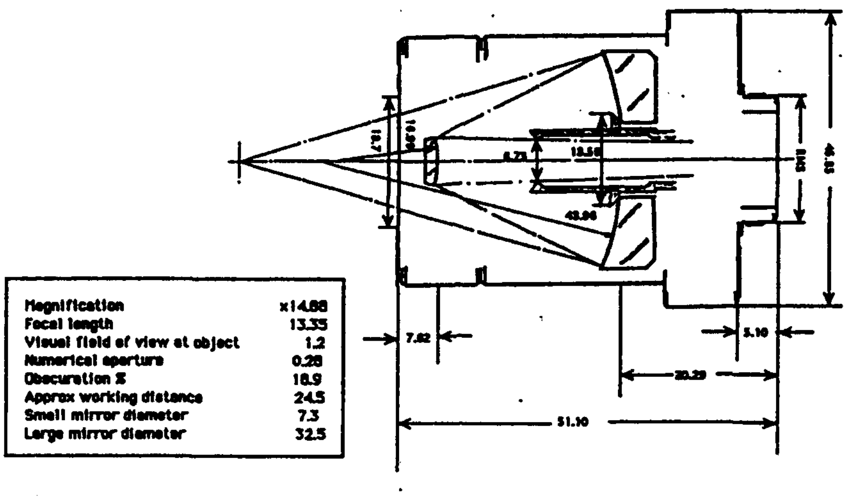


Figure 2. The diagram of the Ealing Schwarzschild objective.

more in x-ray microscopy and lithography[2,7-9] due to itshigher numerical aperture and field size than an x-ray zone plate. Our 33mm diameter, 15X microscope objective fabricated by Ealing Electro-Optics Inc. ( in Figure 2) is designed for compact microscopy and also has the spherical, coma and astigmatic aberration-free qualities. The Schwarzschild objective has a numerical aperture of 0.28 and a focal length of 13.35mm, consisting of two concentric spherical mirrors, a small primary convex mirror (7.3mm radius of curvature) and a large secondary concave mirror (32.5mm radius of curvature). The mirrors are coated with 17nm iridium over 6nm chromium to provide a normal incident reflectivity of up to 26% per surface at 50-60nm. Figure 3 gives the calculated RMS image size versus the object distance for the objective[10]. The best geometrical image with 0.38μm radius is obtained when the object is located 22.80mm in front of the microscope housing. Figure 3 indicates that the a perfectly fabricated objective will exhibit diffraction-limited performance for wavelengths over 130Å when used with this optimum object position.

There are also other advantages in using this reflecting objective in addition to being aberration-free: (1) zero chromatic aberration due to the absence of refractive optical elements, (2) extremely long working distances, (3) large numerical apertures for enhanced light gathering capability, and (4) wide operational wavelength range due to the availability of a variety of reflective coatings.

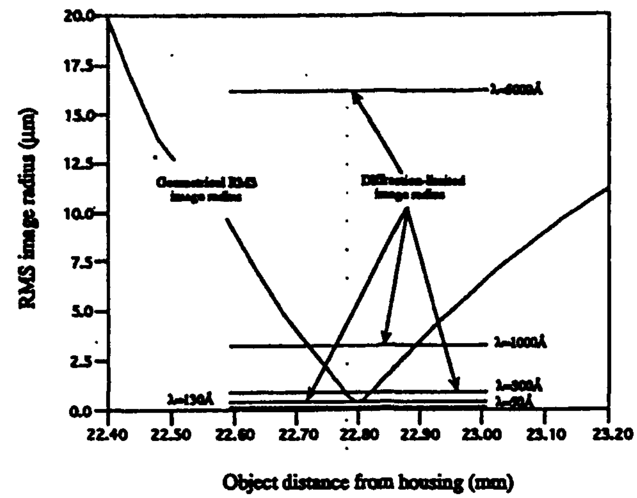


Figure 3. Calculated RMS image size with the object distance for the Schwarzschild objective.

## 4. THE MICROSCOPE

The schematic of the reflection microscope configuration is shown in Figure 4. A 1.06mm Nd:YAG laser beam is directed at a 45° angle with respect to the surface of the tantalum rod which is located in a vacuum chamber. A LPP is produced and emits radiation in the extreme ultraviolet and soft-x-ray spectral region. The radiation, emitted towards the spherical collecting mirror with a solid angle of 0.26 steradian, is reflected and focused on the sample. The radiation through the sample enters the Ealing Schwarzschild which provides a 15X magnified image. The collecting mirror is 2 inches in diameter coated with 17nm of iridium on thick cover glass to provide up to 26% reflectivity at 50-60nm. The EUV/soft x-ray filter is 160nm thick tin and 3% germanium alloy with 20% transmittance at the desired wavelength. Therefore, the flux arrival at the sample would be less than the 10mJ/cm$^2$ damage threshold. The sample holder is mounted on a three axis micro-manipulator which offers maximum three-dimension object movement of 25mm on either of the X or Y stages and 50mm on the Z stage. The chamber is evacuated by an oil-free DRYTEL pumping system capable of operation from atmospheric pressure to $10^{-5}$ Torr.

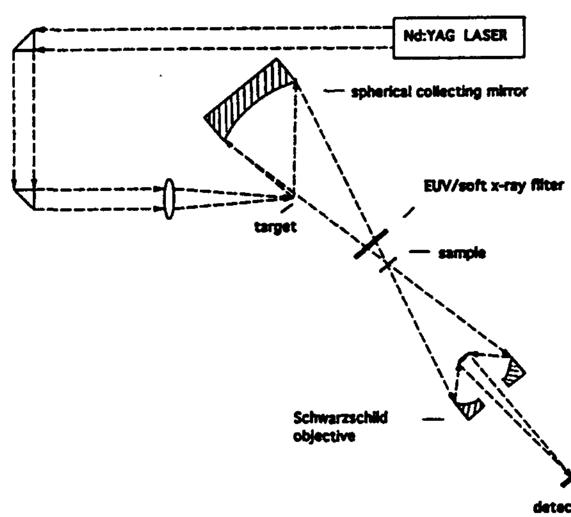


Figure 4. The schematic of the reflection imaging microscope configuration.

Using the diffraction limited resolution formula[7], the resolution of the microscope is approximately

$$W = \frac{1}{2(NA)} . \qquad (1)$$

The depth of focus at the image plane is expressed as

$$DOF = \frac{lM^2}{2(NA)^2} , \qquad (2)$$

where l is the wavelength, NA the numerical aperture, and M the magnification. The microscope parameters are given in Table 1. Figure 5 is a photograph of our reflection imaging microscope.

<u>Table 1</u> Parameters of the EUV reflection imaging microscope.

| | |
|---|---|
| Source to sample Distance | 20.5mm |
| Magnification | 15 |
| Focal Length | 13.35mm |
| Numerical Aperture | 0.28 |
| Expected Spatial Resolution | 0.10μm |
| DOF at image plane | ±67.5μm |
| Expected Flux at sample (at 50-60nm) | $8 mJ/cm^2$ |

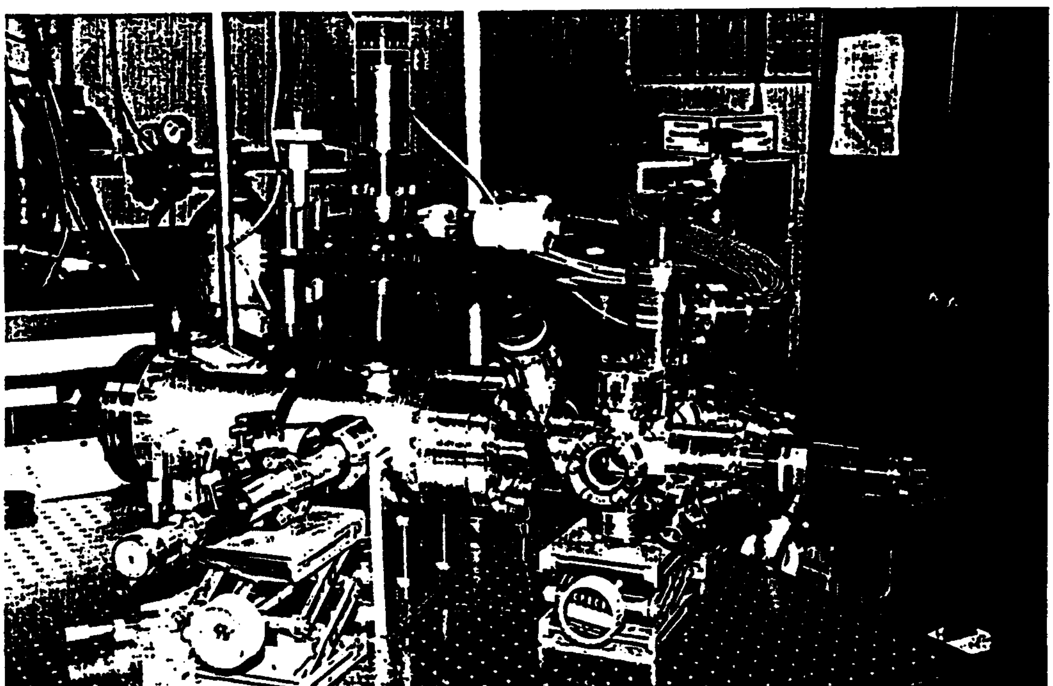

Figure 5. A photograph of the soft x-ray reflection imaging microscope.

The expected flux through the microscope is obtained by the estimated brightness of our current source at 50-60nm, and the efficiency of our Schwarzschild objective and the illuminating optics. The expected flux at the image plane for a laser intensity of $10^{11}$-$10^{12}$ W/cm2 is $2.5 \mu J/cm^2$, which is a sufficient exposure flux loading on the film to produce an image with a single laser pulse. Figure 6 shows the fluorescent image of a Cu 12.5μm mesh pattern obtained by a helium cadmium laser and our present reflection imaging microscope. This image was made for the alignment test only.

When using a LPP as a source for microscopy, one of the most severe problems is the debris problem. The debris particles ablated and emitted from the impact focusing point of the laser beam with the solid target are usually overlooked in the studies of laser-plasma interaction and x-ray lasers. However, in microscopy they are a potential damaging factor to the focusing optics. The debris includes neutrals, ions and clusters and could be in sizes up to tens of microns in diameter and in velocities up to $10^7$ cm/s, depending on the type of target material. It will be deposited on all surfaces facing the target including the illuminating optics. It may not only destroy the fragile components but also deteriorate the focusing performance. So it is desirable to measure the debris in order to minimize the amount of particles reaching the optics.

In our debris measurement, 300μm-thick silicon wafers are used as collecting surfaces for debris. They are placed at the locations of the spherical collecting mirror and Schwarzschild objective. The size and location of the wafers are made to simulate the optical elements in order to collect the equivalent amount of debris under the conditions of the actual imaging experiment. The collecting mirror has the greatest possibility of being damaged since it is in a direct pathway from the source. The larger the NA of the spherical collecting mirror, the more flux is collected from the source, but it is also more difficult to protect the optics from the plasma debris. Figure 7 gives the average number of clusters collected according to the different sizes with 454 shots. As shown in the figure, clusters from 2μm to 6μm in diameter could be observed at the surface of the collecting mirror. However, those particles reaching the collecting mirror will only obscure 0.626% of the surface for every thousand shots. No debris was found where the Schwarzschild surface is located. It also has been found that the debris from the target of tantalum is much less than that obtained from targets of other materials such as Au and Sn[11]. Techniques for interdicting this debris emission before it reaches the illuminating optics are discussed in reference 6.

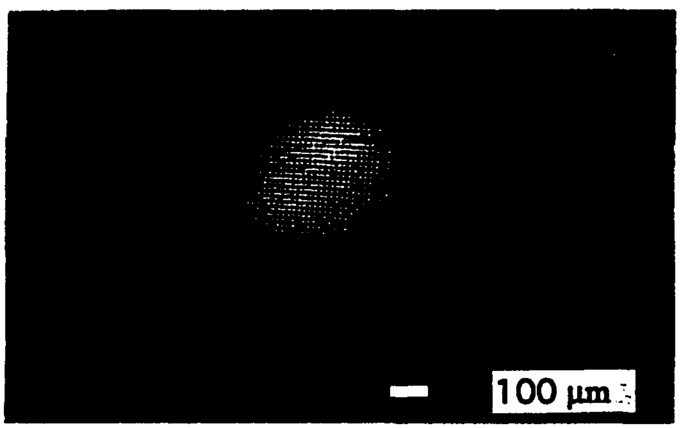


Figure 6. The fluorescent image of a Cu 12.5μm mesh taken by the present microscope and a helium cadmium laser.

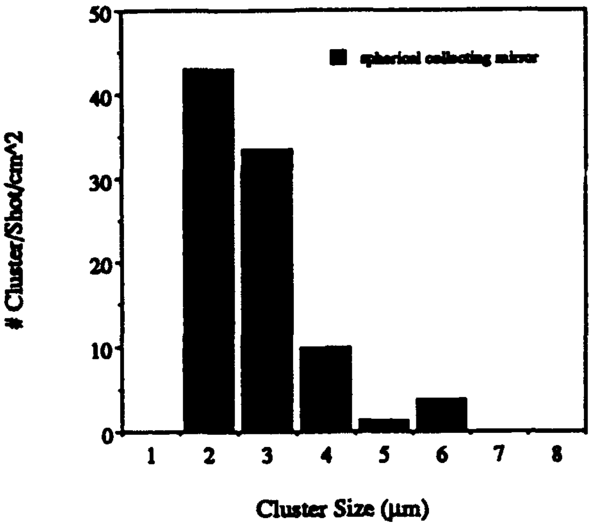


Figure 7. The number and size of the clusters collected in debris measurement with the total 454 shots. Laser energy is ~ 500mJ with the wavelength of 1.06μm and the pulse duration of 10ns. The 1.5mm-diameter tantalum rod is set in a chamber evacuated down to $10^{-4}$ torr.

## 5. DESIGN OF A NEW OFF-AXIS PARTIAL SCHWARZSCHILD OPTIC

We have designed a new off-axis partial Schwarzschild optic that will be used at an illumination wavelength of 13.5 nm. It will have a resolution of 75 nm and a magnification of 200X. The magnification was chosen such that the optic could operate with an array detector having a pixel size of 10 microns. The optic uses spherical mirrors however we also have a version that will achieve a resolution of 50 nm that involves the fabrication of an aspheric optic. This optic will be coated with Mo:Si multilayer reflecting surfaces to obtain high optical efficiency. We are now in the process of getting this optic built.

## 6. CONCLUSIONS

We have constructed a compact EUV reflection imaging microscope that combines high efficiency EUV optics with a high power, short pulsed LPP source. The source is estimated to deliver 145.6mJ/cm$^2$ in a 10ns exposure period. The Schwarzschild objective is a 15X system which has a numerical aperture of 0.28 and a focal length of 13.35mm. The resolution and depth of focus of the microscope would be 0.1μm and ±67.5μm in the region of 50-60nm, respectively. A fluorescent image of Cu 12.5μm mesh taken by the microscope shows the alignment of the present system is sufficient for an imaging experiment. The debris measurements using the present system of the microscope verify that the number of clusters obtained from 2μm to 6μm in diameter is not large enough to significantly damage the optical components. The 50-60 nm wavelength is very appropriate for such a system from the point of view of the source flux, the reflectivity and the transmittance at 50-60 nm. Even so, our next approach will be to scale to 130Å by using a specially designed off-axis partial Schwarzschild objective, and to obtain high resolution images. We have also designed a new off-axis partial Schwarzschild optic to be used at 13.5 nm in combination with multilayer soft-x-ray mirrors.

## 6. ACKNOWLEDGMENTS

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